Photoproduction of J/ψ and Υ in pp and $\overline{p}p$ Collisions

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Exclusive vector meson photoproduction, $pp \rightarrow ppV$ and $\overline{p}p \rightarrow \overline{p}pV$ occurs with significant rates at hadron colliders. The reaction can be used to study the gluon distribution of protons. Vector mesons may be produced with either proton as a target; because of interference between the two production channels, the p_T spectra of vector mesons produced in pp and $\overline{p}p$ collisions are quite different. Because of the unique event signature, vector meson photoproduction can be separated from hadroproduction events, despite the small ratio of cross sections. We consider production of J/ψ and Υ at RHIC, the Tevatron and the LHC.

1. Introduction

Most recent studies of photoproduction have been done with fixed target, real photon beams, or in ep collisions at the HERA collider, where the electromagnetic field of the electron is a source of photons. However, collisions at HERA are limited to photon-proton center of mass energies of about 200 GeV, and no higher energy photoproduction facilities are planned.

However, photoproduction can also be studied at pp and $\overline{p}p$ colliders. These collisions offer some advantages over ep collisions. The Fermilab Tevatron can reach somewhat higher γp energies than HERA, and the LHC can reach more than an order of magnitude higher in energy than HERA. Although photoproduction is a smaller fraction of the total cross section at pp colliders than at HERA, higher machine luminosities can at least partly make up for this. Finally, the CP antisymmetric pp and CP symmetric $\overline{p}p$ initial states allow for some interesting interference effects.

Similar reactions are already studied at heavy ion colliders [1]. The STAR collaboration at RHIC has measured the cross section for $Au + Au \rightarrow Au+Au+\rho^0$ [2], and a significant photonuclear and two-photon physics program is planned for the LHC [3,4]. Cross sections for J/ψ [5,6] and Υ [7] have been calculated. Photonuclear interactions with heavy ions are limited to lower energies than for proton collisions.

Here, we consider photoproduction of J/ψ and Υ at RHIC, the Tevatron, and the LHC. Although it runs at a somewhat lower energy than the Tevatron, RHIC collides polarized protons, allowing for photoproduction studies with polarized targets.

After introducing the ideas behind photoproduction, we will show the rates, rapidity distributions and p_T spectra for these cases. We will also note how this reaction can be used to measure gluon parton distributions down to 10^{-3} at the Tevatron and 2×10^{-4} at the LHC. After discussing the production rates, we will briefly discuss the experimental feasibility of the measurement. Although we focus on vector meson production, other photoproduction reactions should also be accessible at proton colliders.

J/ψ photoproduction in pp collisions has been considered elsewhere [8]. That calculation used a very different approach, focusing on the energy lost by the protons. This makes analytic or numerical comparisons between their result and ours very difficult.

2. Photoproduction

Photoproduction rates depend on two factors: the photon flux, and the photon-proton cross sec-

tion. The cross section is

$$\sigma(pp \rightarrow ppV) = 2 \int dk \frac{dn}{dk} \sigma(\gamma p \rightarrow Vp). \quad (1)$$

where k is the photon energy, dn/dk is the photon flux, and $\sigma(\gamma p \rightarrow Vp)$ is the corresponding photoproduction cross section. The '2' accounts for the fact that either proton/anti-proton can be the emitter or the target.

The photon flux is given by the Weizsäcker-Williams method of virtual photons. For high energy photons, there is a need to consider the proton internal structure. We use the photon spectrum given by Drees and Zeppenfield [9]

$$\frac{dn}{dk} = \frac{\alpha}{2\pi k} \big[1 + (1 - \frac{2k}{\sqrt{s}})^2\big]\big(\ln A - \frac{11}{6} + \frac{3}{A} - \frac{3}{2A^2} + \frac{1}{3A^3}\big) \quad (2)$$

where α is the fine structure constant and

$$A = 1 + \frac{0.71\mathrm{GeV}^2}{Q^2_{min}}. \quad (3)$$

Equation 2 is derived using a proton form factor with $Q^2_{min} = k^2/(\gamma^2(1 - 2k/\sqrt{(s)}))$, where γ is the Lorentz boost of the beam and $\sqrt{s}$ is the proton-proton center of mass energy. This spectrum is close to that of a point charge with a minimum 0.7 fm impact parameter.

For exclusive vector meson production, the photoproduction reaction must not be accompanied by hadronic interactions. To explore this, we consider an alternative photon flux. We eliminate the proton form factor, treating the proton as a point charge, and instead require $b_{min} = 1.0$ fm. This reduces the vector meson production by about 20%; half the difference between these calculations is a reasonable estimate of the systematic uncertainty. A more detailed calculation, including the hadronic interaction probability as a function of b, should lead to a more accurate photon flux, with smaller errors. The photon flux in pp and $\overline{p}p$ collisions can also be studied by considering other photoproduction and two-photon interactions.

The photoproduction cross sections, $\gamma p \rightarrow Vp$ depend on the gluon density in the proton[10]. At mid-rapidity, J/ψ production is sensitive to gluon with x down to 1.5×10^{-3} at the Tevatrony and 2×10^{-4} at the LHC. Away from mid-rapidity, significantly lower gluon energies can be probed.

For cross section estimates, we use data from HERA. Of course, this requires some extrapolation at the Tevatron, and significant extrapolation at the LHC, but that's why the measurement is interesting.

We parameterize the J/ψ cross section[11,12]

$$\sigma(\gamma p \rightarrow J/\psi p) = 1.5W^{0.8}(\mathrm{GeV})\mathrm{nb} \quad (4)$$

where W is the γp center of mass energy. Up to $W \approx 200$ GeV, this is well measured.

The $\Upsilon(1S)$ cross section is parameterized[12, 13]

$$\sigma(\gamma p \rightarrow \Upsilon(1S)p) = 0.06W^{1.7}(\mathrm{GeV})\mathrm{pb}. \quad (5)$$

Neither the absolute values of the cross section nor the energy dependence are well known, so there is considerable room for an improved measurement. The ratio of $\Upsilon(1S)$ to $\Upsilon(2S)$ to $\Upsilon(3S)$ is also unknown; the ZEUS and H1 collaborations assumed that about 70% of the signal was from $\Upsilon(1S)$. This ratio seems to be measurable at the Tevatron.

The photon energy can be determined from the rapidity of the produced vector meson, y:

$$y = \ln(\frac{2k}{M_V}) \quad (6)$$

One complication is that either beam particle is equally likely to produce the photon; the cross sections for these two possibilities are added. Unambiguous determination of the photon energy is possible only at $y = 0$; more sophisticated analyses are needed to determine the cross section for other photon energies. Two promising approaches to moving away from $y = 0$ are to use lower energy data to determine the cross section for the lower energy photon, and to measure the ratio from the two directions by measuring the interference fraction, as discussed below. It may also be possible to use Roman pots or other forward taggers to track the scattered protons; the proton with the larger p_T is very probably the target. This approach could at least partially resolve the two-fold direction ambiguity, and simplify gluon distribution measurements away from $y = 0$.

Here, we consider 3 facilities: pp collisions at $\sqrt{s} = 500$ GeV at RHIC, $\overline{p}p$ collisions at 1.96 TeV

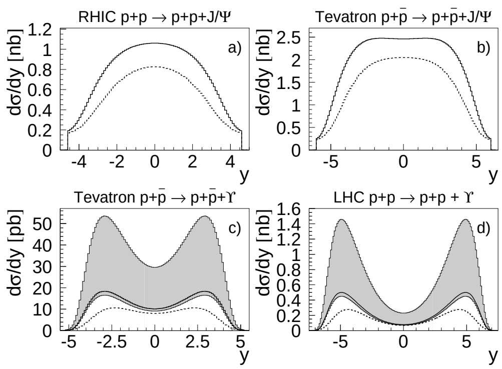

Figure 1. Rapidity distributions, $d\sigma/dy$ for (a) J/ψ production in 500 GeV pp collisions at RHIC, (b) J/ψ production in 1.96 TeV $\overline{p}p$ collisions at the Tevatron, (c) $\Upsilon(1S)$ production in 1.96 GeV $\overline{p}p$ collisions at the Tevatron, and (d) $\Upsilon(1S)$ production in 14 TeV pp collisions at the LHC. The solid histograms are as described in the text. The dashed histogram is done with $b_{min} = 1$ fm, but without the proton form factor (i.e. for a point charge). The shaded regions in (c) and (d) show the cross section uncertainty from the HERA measurements.

at the Tevatron (the results shown at the Small-x and Diffraction 2003 were at $\sqrt{s} = 1.8$ TeV), and pp collisions at 14 TeV at the LHC. We assume luminosities of $10^{31}/\mathrm{cm}^2/\mathrm{s}$, $2 \times 10^{32}/\mathrm{cm}^2/\mathrm{s}$ and $10^{34}/\mathrm{cm}^2/\mathrm{s}$ respectively. With these assumptions, we find the $d\sigma/dy$ shown in Fig. 1. Table 1 summarizes the total cross sections and rates for J/ψ and Υ production.

Lighter vector mesons are also produced prolifically at pp and $\overline{p}p$ colliders. The cross sections for ρ^0, ω and ϕ production should be several orders of magnitude larger than for the J/ψ.

3. Interferometry and p_T spectrum

The vector meson p_T depends on the p_T of the photon and the p_T acquired when the vector meson is produced; the latter is dominant in pp collisions. The p_T of the photon depends on the form

Machine	J/ψ		Υ	
	σ	Rate	σ	Rate
RHIC	7.0 nb	7.0×10^4	12 pb	120
Tevatron	23 nb	4.6×10^7	120 pb	2.4×10^5
LHC	120 nb	1.2×10^{10}	3.5 nb	3.5×10^8

Table 1
Total cross sections and rates for production of the J/ψ and the Υ. The rates are for 10^7 s of running at the Tevatron and the LHC. For RHIC, where most of the running time is devoted to heavy ions, 10^6 s is used.

factor of the proton/anti-proton:

$$\frac{d^3N_\gamma}{d^2k_T dk} = \frac{\alpha F^2(k_T^2 + k^2/\gamma^2)k_T^2}{\pi k(k_T^2 + k^2/\gamma^2)^2} \tag{7}$$

where the form factor

$$F(Q^2) = \frac{1}{(1 + Q^2/0.71\mathrm{GeV}^2)^2} \tag{8}$$

is the same one used previously. Here, k_T is the transverse momentum of the photon. The p_T from the vector meson production is just given by the form factor. We assume that the photon p_T and that obtained in the scattering are randomly oriented.

The final ingredient in the p_T spectrum is an interference term [14]. The two possibilities, proton #1 emitting a photon which scatters off proton #2, and vice versa, are indistinguishable, and so the amplitudes add. The cross section for a given impact parameter, b, is

$$\sigma = |A_1 \pm A_2 \exp{(ip_T \cdot b)}|^2 \tag{9}$$

where A_1 and A_2 are the amplitudes for production for the two possibilities. The exponential is a propagator to account for the phase difference between the two positions. At $y = 0$, $A_1 = A_2$ and the cross section simplifies to

$$\sigma = \sigma_0[(1 \pm \cos{(p_T \cdot b)}] \tag{10}$$

The sign of the interference term depends on the symmetry of the system. For pp (and AA) colliders, one possibility can be transformed into the other via a parity transformation. Vector mesons

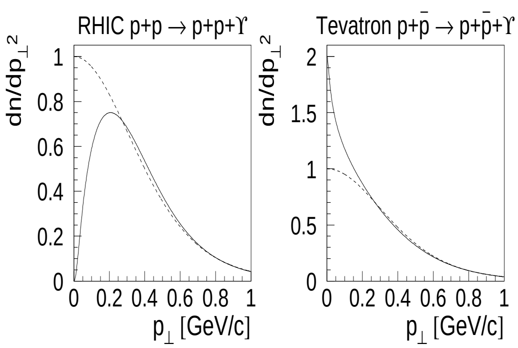

Figure 2. The p_T spectra at mid-rapidity for photoproduced Υ for (left) RHIC and (right) the Tevatron. The solid curves are the predicted spectrum, while the dashed curves are the spectra without interference. The latter curves would be more applicable at large rapidity.

are $J^{PC} = 1^{--}$, *i.e.* negative parity, so the minus sign applies. For $\overline{p}p$ colliders, the requisite transformation is a CP transform, so the plus sign applies.

Of course, the impact parameter b is unmeasurable, so the p_T spectrum is obtained by integrating over b. This washes out the interference except for $p_T < \hbar/\langle b\rangle$ where $\langle b\rangle$ is the mean impact parameter. However, for pp collisions, the mean p_T is not too different from $\hbar/\langle b\rangle$, so the interference has a large effect on the p_T spectrum.

Figure 2 shows the p_T distributions for Υ production at RHIC and the LHC. Because of the different sign of the interference, they look quite different.

4. Experimental Feasibility

As Table 1 shows, the J/ψ rates are high at all 3 accelerators. Even after accounting for leptonic branching ratios and reasonable acceptance estimates, the signals should be large. The Υ rates are high at the Tevatron and the LHC, but, because of the small leptonic branching ratios, are marginal at RHIC.

At RHIC and the Tevatron, the J/ψ and Υ photoproduction cross sections are both about 0.1% of the corresponding hadroproduction cross sections [15,16]. However, because photoproduction is exclusive, $p+p \rightarrow p+p+V$, it should not be difficult to separate the signal from hadronic backgrounds. Three characteristics appear useful in separating the signal: the meson p_T, the presence of rapidity gaps, and the detection of the scattered protons. Here, we focus on the Υ.

Hadronically produced vector mesons typically have $p_T \approx M_V$. A cut on $p_T < 1$ GeV/c eliminates 94% of the hadronic background, while leaving almost all of the photoproduction.

Isolation cuts based on rapidity gaps can provide the remaining separation power. In a hadronic interaction, the probability of having a rapidity gap with with $\Delta\eta$ is $\exp(-\Delta\eta\cdot < dn_{ch}/dy >)$ where $< dn_{ch}/dy >$ is the mean charged particle multiplicity. At RHIC, $< dn_{ch}/dy >= 3$ at $y = 0$, rising to 3.9 at the Tevatron. So, a single gap with width $\Delta\eta = 3$ will reduce the background by a factor of 10^{-4} at RHIC and 10^{-5} at the Tevatron, *i.e.* well below the signal level. This is well within the capability of large detectors. In fact, the situation is better than this, since there will be gaps on both sides of the vector meson.

Exclusive J/ψ production has been seen by the CDF Collaboration in $\overline{p}p$ collisions at the Tevatron[17]. We believe that the origin of these exclusive events is photoproduction in peripheral collisions, as described above.

If they were needed, Roman pots could be used to detect the scattered protons, gaining cleanliness at some cost in detection efficiency. One attractive feature of using Roman pots is that if the proton p_T can be measured, it should provide some information on which proton emitted the photon, and which was the scattering target.

Cuts on rapidity gaps are less effective in rejecting other diffractive interactions. However, vector mesons have the wrong quantum numbers to be produced in double-Pomeron interactions. One background is double-Pomeron production of the χ_{c0} or χ_{b0}, decaying to $\gamma J/\psi$ or $\Upsilon\gamma$, where the photon is missed. At the Tevatron,

the double-Pomeron cross sections for the χ_{c0} and χ_{b0} are about 600-735 nb and 0.1-0.9 nb respectively[18,19]. After accounting for the branching ratio, these backgrounds are small for the J/ψ, and very probably small for the Υ. Also, the p_T for double-Pomeron produced mesons is considerably larger than for photoproduction.

The photoproduction cross section rises with beam energy much more rapidly than the soft Pomeron trajectory, so the ratio of photoproduction to hadronic interactions, both diffractive and non-diffractive, should grow as the beam energy increases. This is why photoproduction could not be observed in lower energy, fixed target, experiments. Conversely, it should be even more important at the LHC.

5. Conclusions

The rates for photoproduction of J/ψ and Υ mesons in pp and $p\overline{p}$ collisions at RHIC, the Tevatron and the LHC are high, and these reactions can be used to measure the gluon content of the proton at low x values. The p_T spectrum of the produced vector mesons are quite different at pp and $p\overline{p}$ colliders. The hadronic backgrounds to these reactions can be controlled by selecting events with low p_T vector mesons in an otherwise empty detector.

Photoproduction of other channels may also be of interest at hadron colliders. The cross sections for different photoproduction channels rise rapidly with beam energy, in contrast to most diffractive channels. So, as accelerator energy progresses, photoproduction will become more and more important.

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